Bayesian Cloud Property Retrievals from ARM Active and Passive Measurements

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1. Introduction and Scientific Background

Cloud processes remain a major source of uncertainty in regional and global modeling of the Earth's climate system. Not only do they have a key effect on the flow of radiative energy, but they also exert an important influence on the interaction between dynamic systems and the larger scale environment. Cloud microphysics lies at the heart of this uncertainty, as it (1) governs the rates of conversion between phases of water, (2) modulates the amount of water transported vertically from the boundary layer to all levels of the troposphere, and (3) determines the properties of particles at cloud top and in the cloud interior. The availability of long-term estimates of microphysical properties (e.g., water content, characteristic size) with well-characterized uncertainties is key to our efforts to evaluate and improve the representation of clouds and precipitation in numerical models.

The overarching goal of the DOE Atmospheric System Research (ASR) program is to advance the understanding of cloud-precipitation-aerosol-radiation interactions and contribute to the improvement of their representation in numerical models. The optimum use of the continuous measurements of thermodynamics, radiation, aerosols, clouds and precipitation from the DOE Atmospheric Radiation Measurement (ARM) program is key to achieve ASR's objectives. One of the key mission requirements is to retrieve cloud and precipitation properties, as well as vertical motion parameters, along the vertical cross-section defined by the profiling active sensors. Such retrievals are challenging to perform continuously in the entire spectrum of cloud and precipitation conditions due to the large natural microphysical and dynamical variability, the often-limited information content in the measurements, and the lack of proper characterization of measurement quality and uncertainty. Today, the acquisition of new remote and in-situ sensors by the ARM program creates opportunities to address the microphysical retrieval problem by exploiting new, more robust retrieval techniques and integrating various scattered advancements in both sensor techniques and retrieval algorithms.

ARM is not new to the development of column microphysical and dynamical retrievals. Since the early days of the ARM program, PI's have developed retrieval algorithms and produced PI products (e.g., Mace and Benson, 2008; Shupe et al. 2008; Kalesse and Kollias, 2013). In parallel, ARM supported the development of the MICROBASE Value-Added Product (VAP), its own baseline retrievals of cloud microphysics (Dunn et al., 2011). However, MICROBASE is based on very simplified, outdated algorithms that work adequately only in a limited spectrum of clouds and precipitation conditions. Furthermore, no uncertainty quantification is provided. In an attempt to address the latter issue, there have been significant efforts in ARM to understand retrieval uncertainties and improve retrieval accuracy

Our work has demonstrated that microphysical retrievals based on Bayesian methodologies have promise for producing robust estimates of cloud PSD properties, and for returning quantitative measures of uncertainty in the retrievals (Posselt et al. 2008; Posselt and Mace 2014; Posselt et al. 2017).

During this project, we constructed a robust Bayesian Markov chain Monte Carlo (MCMC) cloud property retrieval algorithm that includes a state of the art radar forward model. Our MCMC-based retrieval produces both the best estimate of height-resolved cloud and precipitation properties in the radar profile, as well as an estimate of the in-cloud vertical motion and turbulence. In addition, the MCMC algorithm automatically produces robust and flexible estimates of retrieval uncertainty. We tested the algorithm on several synthetic cloud profiles obtained from large eddy simulation (LES) models with bin-resolved microphysics.

2. Results

In our DOE funded research, we expanded on the work of PM14, and designed a new two-frequency (W- and Ka-band) MCMC-based retrieval of liquid cloud properties. As in PM14, this retrieval uses the

Bayesian MCMC framework to retrieve the full multivariate probability distribution of the liquid water content, droplet number concentration, and effective radius for two cloud modes. However, we have replaced the simpler radar forward model used in PM14 with the McGill Radar Doppler Spectra Simulator (MRDSS). MRDSS produces a simulated Doppler spectrum using input particle size distribution properties resolved into various size bins. In our work, we populate these bins with a bimodal analytical modified gamma particle size distribution (one mode for each of the cloud and precipitation species). MRDSS accounts for gaseous attenuation and liquid (Mie) scattering, and can be run for a wide range of radar frequencies. In addition, the code can be used to simulate the key characteristics of the radar, including antenna size, receiver noise, and signal integration. The Signal-to-Noise Ratio (SNR) is used to determine the amount of noise added throughout the spectrum and the spectral smoothing due to spectral averages is included to reproduce the averaging realized by cloud radars on successive returns. Thus, realistic Doppler spectra are obtained, and several parameters that relate to the morphological characteristics of the synthetically generated spectra are computed using the same algorithm used by ARM to develop the micro-ARSCL VAP. We converted the MRDSS code from MatLAB to Fortran, and verified that the two versions produce identical results to within machine precision.

2.1 *Retrieval Results*

Our tests of the new algorithm utilized synthetic cloud profiles obtained from large eddy simulations of shallow convection during the CAP-MBL experiment over the Eastern North Atlantic ARM site. Bin resolved microphysics from the SAMEX model was used to produce simulated W- and Ka-band Doppler spectra, including reflectivity, mean Doppler velocity, Doppler spectral width, skewness, and kurtosis. We then used the simulated radar moments to retrieve vertical profiles of 2-mode cloud properties. We tested the information content of the measurements by conducting retrievals using the following combinations of measurements:

1. W-band reflectivity only
2. W-band reflectivity and Doppler velocity
3. W-band and Ka-band reflectivity
4. W-band and Ka-band reflectivity and Doppler velocity

Slices through all 6 dimensions of the probability distribution of retrieved cloud properties for one layer in the profile are shown in Figs. 1 and 2 for experiments (2) and (4) above, respectively. These results demonstrate the need for Doppler velocity to provide constraint of both particle modes; when reflectivity alone is used, particle size is well constrained, while number and liquid water content are not. When Doppler velocity is used as an additional constraint, the solution is unique.

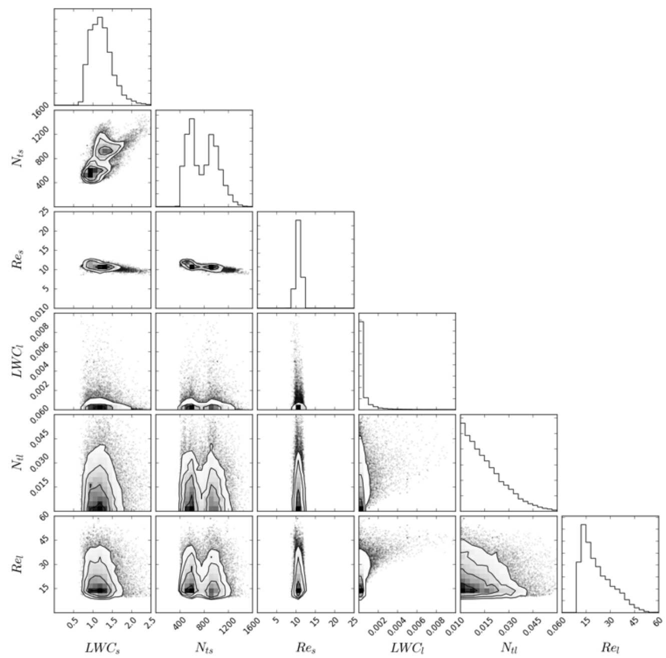

Fig. 1: Two dimensional marginal probability distributions for each pair of retrieved parameters: liquid water content (LWC), number concentration (Nt), and effective radius (Re). The subscripts denote "small" (s; non-precipitating) and "large" (l; precipitating) modes. Contours depict regions of increasing probability mass from 37% (inner) to 68% (middle) to 95% (outer). Univariate marginal distributions are depicted on the diagonal. W-band and Ka-band reflectivity are used as constraints.

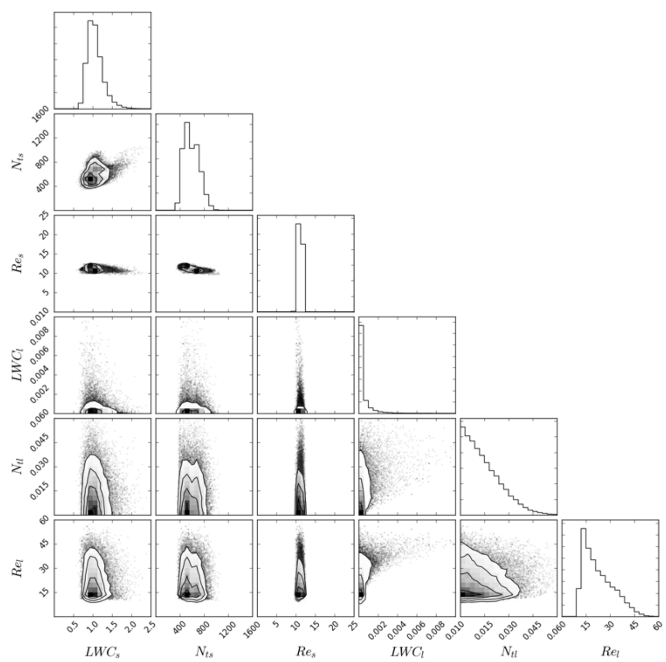

Fig. 2: As in Fig. 1, but for observations of W-band and Ka-band reflectivity and Doppler velocity.

2.2 *Uncertainty Quantification*

Our retrieval assumes that the arbitrarily complex drop size distribution (DSD) in the model (as represented in the bin resolved microphysics) can be approximated via a two-mode (non-precipitating and precipitating) gamma distribution of drops. This inevitably leads to errors in the retrieval, as there will be cases for which the gamma distribution is not a good fit to the real DSD. As such, in addition to producing retrieved cloud properties, we also estimate the uncertainty in radar Doppler moments (e.g., reflectivity, mean Doppler velocity, spectrum width, skewness, and kurtosis) caused by the gamma DSD assumption. We do this by constraining the 6 parameters of the 2-mode gamma DSD using moments obtained from the "true" DSD (bin microphysics), where moments are defined as

$$M_x = \int_0^{D_{max}} D^x N(D) dD$$

Uncertainty in all moments is assumed to be 1 dB, and we use MCMC to estimate the PDF of the PSD parameters given the bin DSD as "observations". The prior distribution is assumed to be uniform in $\log_{10}$ N_0, D_0, and alpha for each mode, with a restriction that the cloud mode has a smaller effective radius than the precipitating (rain/drizzle) mode. Fitting a 2-mode DSD to the "true" bin DSD results in errors in the radar Doppler spectrum moments (Fig. 3). These errors need to be included in the radar retrieval uncertainty estimate.

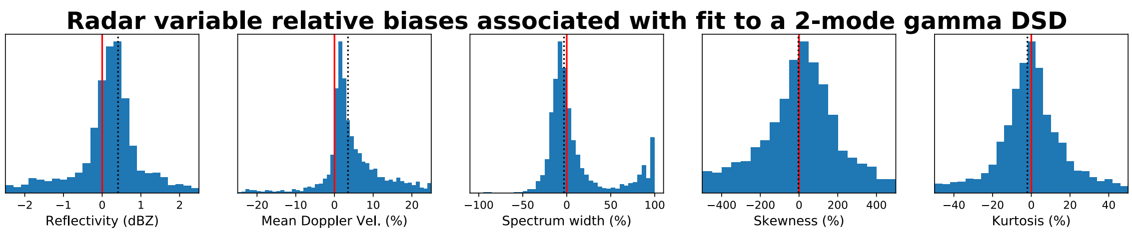

Fig. 3: Histograms of radar reflectivity, doppler velocity, spectrum width, skewness, and kurtosis associated with fits of the 2-mode gamma distribution to the bin microphysics PSD.

The key points that may be derived from our research include the following:

1. MCMC is capable of elucidating the characteristics of the true solution space without resorting to a lookup table or assumptions about the form of the PDF.
2. MCMC can be used to quantify the effect of errors in the forward model(s) and PSD assumptions, and can compute the benefit of information from additional measurements.
3. Our work indicates we may be able to uniquely constrain vertical profiles of cloud and drizzle mode using two frequency radar with Doppler.

Roles of investigators:

The Principal Investigator, Dr. Derek Posselt, was responsible for the planning and execution of all phases of this project. He was responsible for the analysis of the MCMC-based cloud property retrievals.

Co-Investigator Dr. Pavlos Kollias supervised a post-doc, who provided assistance with the radar forward model and uncertainty quantification.

Co-Investigator Dr. Marcus van Lier-Walqui was responsible for implementing the radar forward model on the LES output, running MCMC experiments, and analyzing the results. He will served as point-person for synergistic collaboration with Drs. Fridlind and Ackerman at NASA GISS.

4. Project Objectives and Relevance to Goals of the ASR Program

The primary objective of this project was to develop a new Bayesian cloud property retrieval algorithm suitable for use with ground-based instrumentation at the DOE ARM sites. The work represented the first time a fully Bayesian algorithm has been used in the ARM program, and the first time an MCMC algorithm has ever been systematically used to retrieve vertical profiles of cloud properties. Production of the full joint probability distribution of cloud properties allows a more in depth analysis of the relationships between cloud properties in-cloud and with the surrounding environment. Bayesian retrieved quantities naturally have robust measures of uncertainty derived from the posterior probability distribution. These uncertainty measures are more thorough and accurate than any that have yet been available from either ground-based or space-borne remote sensing systems.

The secondary objective was to assess the information content of the first and second generation of the new ARM scanning cloud radars (SACR and SACR2), as well as whether a single frequency radar is capable of retrieving cloud properties under a restricted range of conditions or alongside an appropriate prior assumption.

The research directly addressed the following goals of the ASR program:

1. Develop and evaluate an algorithm that retrieves cloud microphysics in shallow cumuli clouds using the next generation of measurements at the SGP and ENA ARM sites.
2. Produce retrieval algorithms that return the full joint probability distribution of cloud properties distributed in the vertical.
3. Determine information content of current ARM observational systems, and assess their potential use in evaluation of LES/CRM/GCM simulations.
4. Return robust uncertainty estimates for current suites of ARM measurement platforms.